Properties of Cluster Radio Emission

Luigina Feretti

Istituto di Radioastronomia CNR, via P. Gobetti 101, 40129 Bologna, Italy
e-mail: `lferetti@ira.cnr.it`

Abstract. Relevant studies of the non-thermal components of the intracluster medium are performed at radio wavelengths. A number of clusters, indeed, exhibits cluster-wide diffuse radio emission, which is indication of the existence of large scale magnetic fields and of relativistic electrons in the cluster volume. There is strong evidence that the presence of diffuse radio emission is related to cluster merger processes. The details of the halo-merger connection are discussed and a brief outline of current models of halo formation is presented.

Key words. Clusters of Galaxies – Intracluster medium – Radio Emission

1. Introduction

The main components of clusters of galaxies are the galaxies (2-3%), the hot gas (13-15%) and the dark matter (82-85%). In addition, a relativistic component may be present which plays an important role in the cluster formation and evolution. The most detailed studies of this component come from the radio observations. A number of clusters of galaxies is known to contain large-scale diffuse radio sources which have no obvious connection with the cluster galaxies, but are rather associated with the intracluster medium (ICM). These sources are classified in two groups, radio halos and relics, according to their location at the cluster center or cluster periphery, respectively. The synchrotron origin of the emission from these sources requires the presence of cluster-wide magnetic fields of the order of ~ 0.1-1 μG, and of a population of relativistic electrons with Lorentz factor $\gamma >> 1000$ and energy density of $\sim 10^{-14}$-10^{-13} erg cm^{-3}.

The importance of halos and relics is that they are large scale features, related to other cluster properties in the optical and X-ray domains, and thus connected to the cluster history and evolution.

These sources are found in clusters which have recently undergone a merger event, thus leading to the idea that they originate from particle acceleration in cluster merger turbulence and shocks. The formation and evolution of these sources is however still under debate: the radio emitting electrons could be reaccelerated cosmic rays, or accelerated from the thermal population, or could be produced as a result of the interaction between cosmic-ray protons and the ICM. We summarize the current knowledge on these sources from an observational point of view.

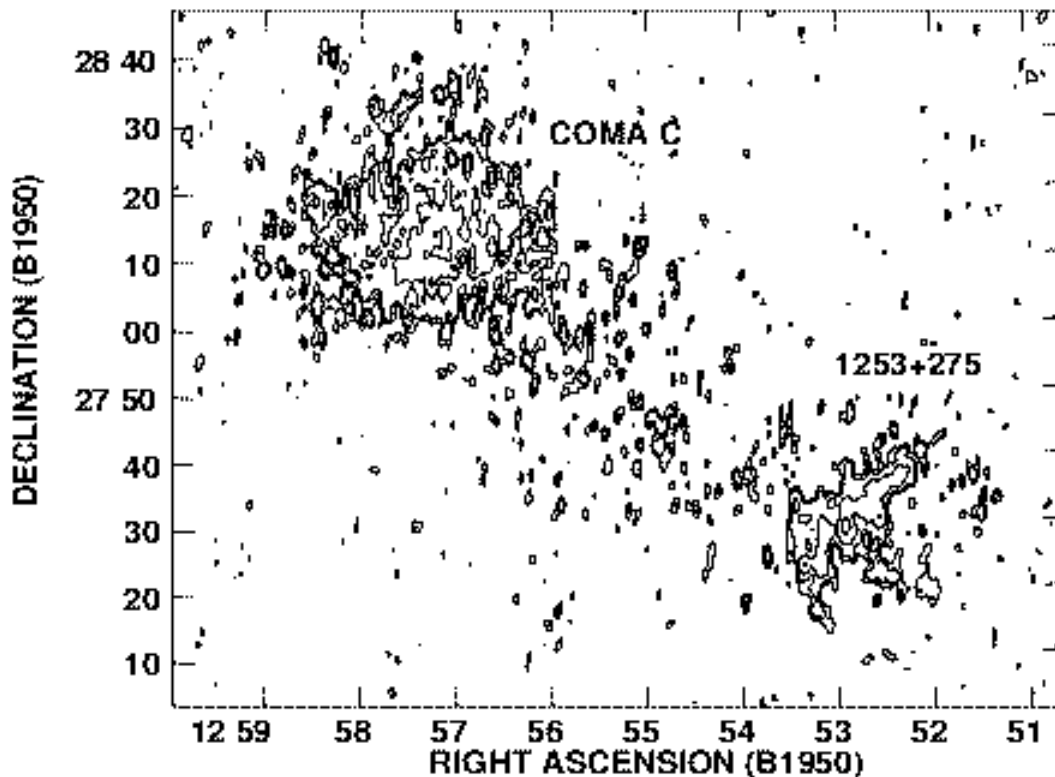The instrinsic parameters quoted in this paper are computed with a Hubble con-

Fig. 1. Diffuse radio emission in the Coma cluster, obtained at 90 cm with the Westerbork Synthesis Radio Telescope. The discrete sources have been subtracted. The cluster center is approximately located at the position $RA_{1950} = 12^h\ 57^m\ 24^s$, $DEC_{1950} = 28°15'00''$. The radio halo Coma C is at the cluster center, the radio relic 1253+275 is at the cluster periphery. An angular size of $10'$ corresponds to a linear size of ~ 400 kpc. Contour levels are at 2.5, 4, 8, 16 mJy/beam (FWHM = $55'' \times 125''$; RA $\times$ DEC).

stant $H_0 = 50$ km s^{-1} Mpc^{-1} and a deceleration parameter $q_0 = 0.5$.

2. Radio halos and relics: the Coma cluster

The Coma cluster is the first cluster where a radio halo and a relic have been detected (Willson 1970, Ballarati et al. 1981). The halo in this cluster, Coma C (see Fig. 1), is the prototypical example of halo sources: it is located at the cluster center, it is characterized by a regular shape with a total extent of ~ 1 Mpc, and by a low radio surface brightness ($\lesssim\ \mu$Jy arcsec^{-2} at 1.4 GHz). It is unpolarized down to a limit of a few percent, and shows a steep radio spectrum, typical of aged radio sources ($\alpha \gtrsim 1$), with a steepening at higher frequencies (Fig. 2). The spectral index distribution of Coma C
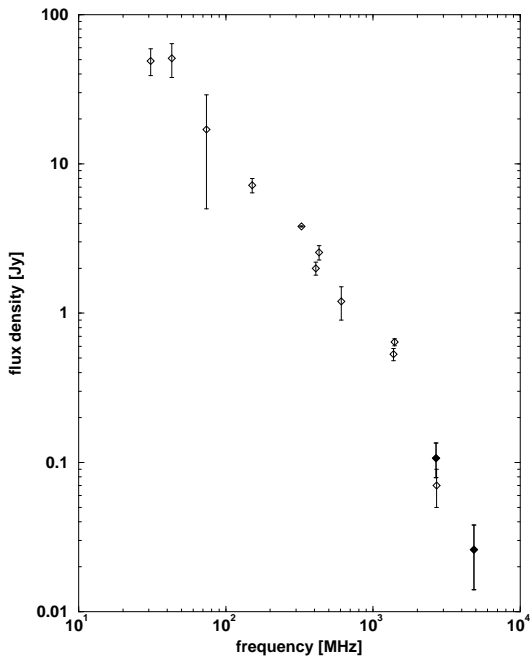
Fig. 2. Total radio spectrum of the radio halo Coma C (from Thierbach et al. 2003).
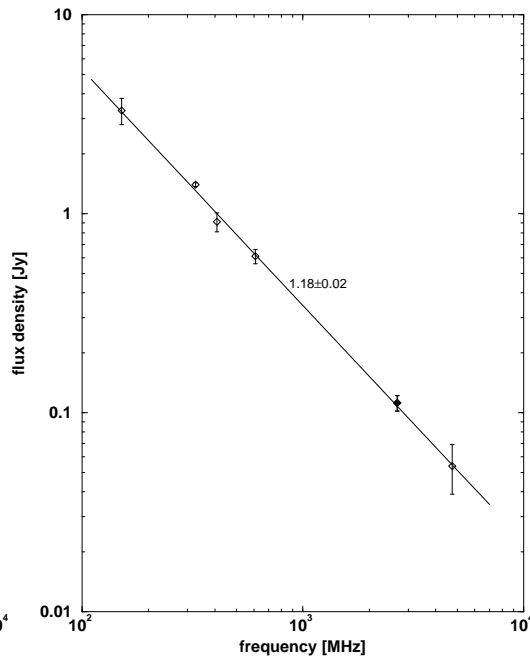
Fig. 3. Total radio spectum of the relic 1253+275 (from Thierbach et al. 2003).

shows a radial decrease (Giovannini et al. 1993) from $\alpha \sim 0.8$ at the cluster center, to $\alpha \sim 1.8$ beyond a distance of about $10'$. By assuming that there is energy equipartition between relativistic particles and magnetic field, a minimum energy density of $1.62 \; 10^{-14}$ erg cm^{-3} is derived from the radio data. The corresponding equipartition magnetic field is 0.4 μG.

The radio source 1253+275 in the Coma cluster (Fig. 1) is the prototype of the class of radio relics, which are extended diffuse radio sources associated with the ICM, located in the cluster peripheral regions. This source is similar to the halo Coma C in its low surface brightness, large size and steep spectrum (Fig. 3). Unlike halos, it shows an elongated structure and it is highly polarized ($\sim 25\%$).

The radiative lifetime of the relativistic electrons in Coma C, considering synchrotron and inverse Compton energy losses, is of the order of 10^8 yr. This is

too short to allow the particle diffusion throughout the cluster volume. This implies that the radiating electrons cannot have been injected at some particular point of the cluster, but they must undergo *in situ* energization. This is a general problem for all the halo and relic sources. Feretti (2002) argued that halos and relics are not the same objects seen in projection, i.e. halos are really at the cluster center and not simply projected onto it. Halos and relics may indeed have different physical origins.

Coma is one of the few clusters where hard X-ray emission has been detected with the BeppoSAX and Rossi X-ray Timing Explorer (RXTE) satellites (Fusco-Femiano et al. 2004 and references therein). This emission is expected in clusters with diffuse radio sources, as the high energy relativistic electrons responsible for the radio emission ($\gamma \sim 10^4$) scatter off the cosmic microwave background, boosting photons from this radiation field to the hard X-
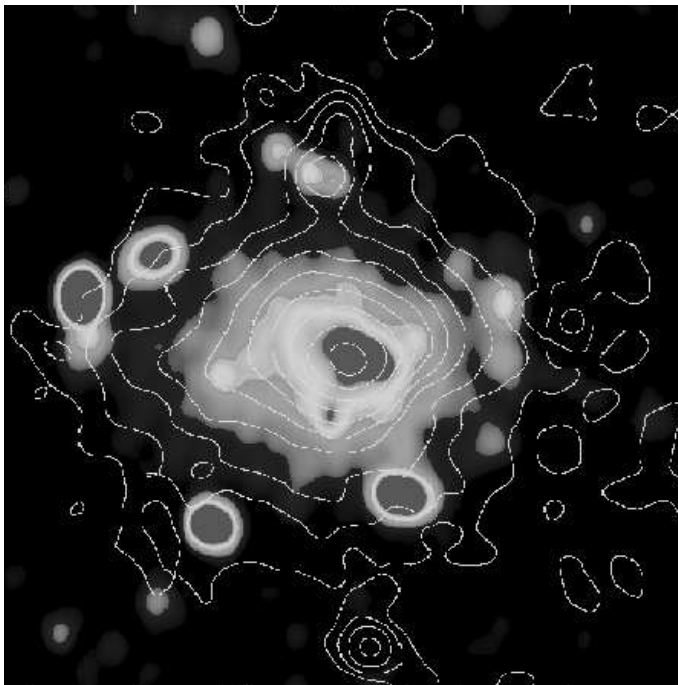
Fig. 4. The cluster A2163 in radio and X-ray. The grey scale image represents the radio emission in A2163 at 20 cm, showing an extended radio halo. The contours represent the ROSAT X-ray emission. The extended irregular X-ray structure indicates the presence of a recent cluster merger.

ray domain by inverse Compton (IC) process. Measurements of this radiation provide additional information that, combined with results of radio measurements (i.e. the ratio of hard X-ray IC emission to radio synchrotron emission), enables the determination of the electron density and mean magnetic field directly, without invoking equipartition.

The 20-80 keV flux in Coma is ~ 1.5 10^{-11} erg cm^{-2} s^{-1}, which leads to a volume averaged intracluster magnetic field of ~ 0.2 μG (Fusco-Femiano et al. 2004). This value is consistent with that obtained by the radio emission assuming equipartition (see above). It is inconsistent, however, with the value of ~ 6 μG deduced by Feretti et al. (1995) from Faraday Rotation Measure (RM) data (see Sect. 4).

It is worth mentionining here that alternative models have been suggested to explain the hard X-ray tails (e.g. non-thermal bremsstrahlung). These models were motivated by the discrepancy between the value of the ICM magnetic field derived by the IC model and the value derived from RM. However, these models may have serious difficulties as they would require an unrealistic high energy input (Petrosian 2001).

3. Connection to cluster merger processes

Unlike the thermal X-ray emission, the presence of diffuse radio emission is not common in clusters of galaxies. In a complete sample, 5% of clusters have a radio halo source and 6% have a peripheral relic source (Giovannini & Feretti 2002). The detection rate of diffuse radio sources increases with the cluster X-ray luminosity,

reaching $\sim 35\%$ in clusters with X-ray luminosity larger than $\sim 10^{45}$ erg s^{-1}.

The optical and X-ray observations indicate that halo and relic clusters contain strong evidence of dynamical evolution (Giovannini & Feretti 2002). An example is represented by the cluster A2163, which hosts a powerful radio halo (Feretti et al. 2001), shown in Fig. 4. The connection between the formation of halos and relics and the presence of recent/ongoing mergers in the clusters is consistent with the relative rarity of diffuse sources, and the lack of diffuse sources in clusters showing a massive cooling flow. Cluster mergers are among the most energetic phenomena in the Universe, releasing gravitational binding energies of about 10^{64} erg. They generate shocks, bulk flows, turbulence in the ICM. These processes would provide energy to reaccelerate the radiating particles all around the cluster.

The most recent investigations of the details of the connection between radio halos and cluster mergers are presented in the following.

Fig. 5. Plot of the radio brightness versus the X-ray brightness, for the radio halo in A2163 (shown in Fig. 4). Each point represents the brightness mean in cells of $90''$ in size, while the error bars indicate the rms in each cell. The best fit, indicated by the solid line, corresponds to the relation $F_{radio} \propto F_{Xray}^{0.64}$ (from Feretti et al. 2001).

3.1. Correlation between radio and X-ray brightness

The comparison between radio and X-ray images of clusters reveals that there is often a close similarity on large scale between radio and X-ray structures. Govoni et al. (2001) first performed a quantitative point-to-point analysis of the halo radio brightness F_{radio} and the cluster X-ray brightness F_{Xray}. They obtained a power law relation of the type: $F_{radio} = aF_{Xray}^b$, with values of b between 0.6 and 1. An example of the above relation is given in Fig. 5. Since the structure of the X-ray emission is generally related to a cluster merger process, a close connection between the structure of the halo and that of the X-ray gas supports a connection between the halo radio emission and the merger.
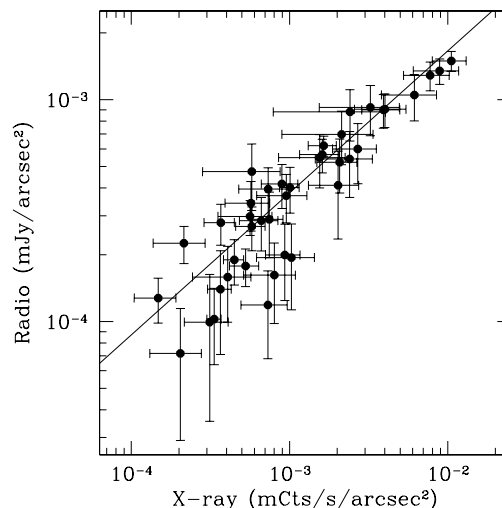
3.2. Comparison between radio emission and gas temperature

High resolution Chandra X-ray data have been recently obtained for several clusters with halos or relics. In all these clusters, temperature gradients and gas shocks are detected confirming the presence of mergers (Markevitch & Vikhlinin 2001, Markevitch et al. 2003, Govoni et al. 2004). In some clusters there is a correlation between the radio halo emission and the hot gas regions (Govoni et al. 2004). Although it may be difficult to disentangle the geometry of the cluster merger, it can be generally concluded that merger shocks and turbulence are the relevant acceleration mechanisms for the halo generation.
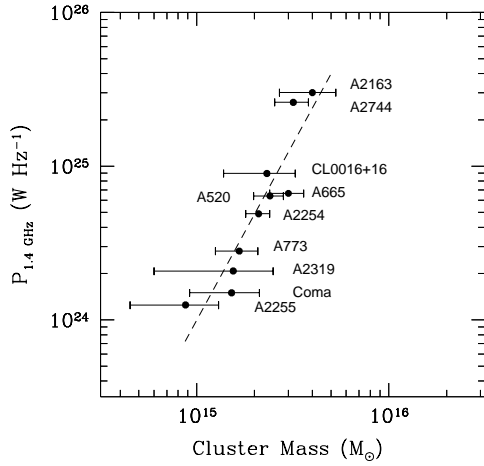
Fig. 6. Halo monochromatic radio power at 1.4 GHz versus total gravitational mass within 3 Mpc radius. All the data are from ROSAT, except A2163 from XMM (Arnaud, priv. comm.). The best fit line (dashed) is $P_{1.4GHz} \propto M^{2.3}$.

3.3. Connection between radio spectrum and X-ray features

Maps of the radio spectral index represent a powerful tool to study the properties of the relativistic electrons and of the magnetic field in radio sources. Preliminary maps of the radio spectral index between 0.3 GHz and 1.4 GHz of the radio halos in A665 and A2163 (Feretti et al. in preparation) show a different behaviour across the regions presently interested by the ongoing merger and the relatively undisturbed regions. The synchrotron spectrum is flatter in the merging regions, indicating that the radio emitting electrons are more energetic here. In the more relaxed regions, the spectral index steepens progressively with the distance from the cluster center. This global behaviour indicates that the energy of radio halos is sensitive to the effects of mergers.

3.4. Connection between radio power and cluster mass

The energy available from a merger is approximately proportional to the squared cluster mass M^2. From simple arguments, it is deduced that the energy released in a merger shock is proportional to the gas density ρ and to the subcluster velocity v^3. Since $\rho \propto M$, and $v \propto M^{1/2}$, one obtains that roughly $\dot{E} \propto M^{5/2}$ (see also Kempner & Sarazin 2001). Fig. 6 shows that a correlation exists between the halo monochromatic radio power P at 1.4 GHz and the total gravitational cluster mass. The best fit is $P_{1.4GHz} \propto M^{2.3}$. This is similar to what expected from the above simple considerations, thus favouring the hypothesis that the radio halo is powered by the energy released in the cluster merger.

4. How common are magnetic fields in clusters

Besides the direct evidence obtained from the synchrotron emission, the existence of cluster magnetic fields can be indirectly probed by Rotation Measure studies of radio galaxies embedded within the cluster thermal atmospheres or located behind them.

This kind of studies has been performed on several individual clusters, with or without cooling flows, e.g. Coma, A119, A514, A2255, 3C129, 3C295, Hydra A, as well as on statistical samples (see the review by Carilli and Taylor 2002, and references therein). In general, the suggestion from the data is that magnetic fields in the range of 1-5 μG are common in clusters, regardless of the presence of diffuse radio emission. At the center of cooling flow clusters, magnetic field strenghts can be larger, up to 10-30 μG.

Another result of the above mentioned studies is that the RM distributions tend to be patchy with coherence lenghts of 2-10 kpc, indicating that the magnetic fields are not ordered on cluster scales, but consist of cells with random field orientation.

The magnetic field intensity in clusters shows a radial decline. This has been deduced in Coma (Brunetti et al. 2001) and in A119 (Dolag et al. 2001). In the latter cluster, the magnetic field intensity scales with the gas density n_e as $n_e^{0.9}$.

The magnetic field strengths obtained from RM studies are about an order of magnitude higher than the equipartition values obtained from the radio data, or those derived from the hard X-ray IC emission (Sect. 2).

However, the different measurements of the magnetic fields could reflect the value of the field in different regions of the clusters. For example, since the magnetic field strength has a radial decrease, most of the IC emission will come from the weak field regions in the outer parts of the cluster, while most of the Faraday rotation and synchrotron emission occur in the strong field regions in the inner parts of the cluster. Moreover, the magnetic field inferred from RM data could be affected by local magnetic field compression and enhancements (Rudnick & Blundell 2003).

Recent modeling by Govoni & Murgia (2004) shows that the presence of magnetic field substructure and/or filamentation can lead to significant differences between field estimates obtained from different approaches. Thus the above mentioned discrepancies can be at least partially solved if a more realistic magnetic field geometry is taken into account.

5. Models for Relativistic Particles

A population of relativistic electrons can account for the radio emission in radio halos and the hard X-ray emission in clusters via synchrotron and inverse Compton processes, respectively. Current models have been reviewed by Brunetti (2003). The relativistic particles could be injected in the cluster volume from AGN activity (quasars, radio galaxies, etc.), or from star formation in normal galaxies (supernovae, galactic winds, etc). Most of the particle production has occurred in the past and is therefore connected to the dynamical history of the clusters. This population of *primary electrons* needs to be reaccelerated (Brunetti et al. 2001, Petrosian 2001) to compensate the radiative losses. A recent cluster merger is the most likely process acting in the reacceleration of relativistic particles.

Another class of models for the radiating particles in halos involves *secondary electrons*, resulting from inelastic nuclear collisions between the relativistic protons and the thermal ions of the ambient intracluster medium. The protons diffuse on large scale because their energy losses are negligible. They can continuously produce in situ electrons, distributed through the cluster volume (Blasi & Colafrancesco 1999, Miniati et al. 2001).

A strong observational evidence in favour of primary electron models is the behaviour of radio spectra in halos. The high frequency steepening observed in Coma (Thierbach et al. 2003) and in A754 (Bacchi et al. 2003, Fusco-Femiano et al. 2003), and the radial steepening observed in Coma (Giovannini et al. 1993), A665 and A2163 (Sect. 3.3) can be easily reproduced by models invoking reacceleration of particles. On the contrary, the spectral index trends are difficult to explain by models considering secondary electron populations. Other arguments favouring primary electron models are the observed link between radio halos and cluster mergers, the slope of the correlation between radio and X-ray brightness (see Govoni et al. 2001 for details), and the relatively low number of clusters with halos. On the other hand, strong γ-ray emission, which should be detected by future γ-ray instruments, is expected to be produced in the framework of secondary electron models, thus providing an important test for the origin of the electrons radiating in radio halos.

Different models have been suggested for the origin of the relativistic electrons radiating in the radio relics, i.e. located in confined peripheral regions of the clusters. There is increasing evidence that the relics

are tracers of shock waves in merger events (Enßlin et al. 1998), confirming that the cluster merger is the most important ingredient for the formation of any type of diffuse radio emission.

6. Conclusions

The existence of cluster-wide diffuse radio emission indicates that there are important non-thermal components in the ICM: magnetic fields and relativistic particles. The presence of magnetic fields in galaxy clusters is additionally demonstrated by RM studies, which indicate that magnetic fields are rather common in all clusters, not only those with radio halos. There is convincing evidence that radio halos and relics are linked to cluster merger processes. Violent mergers provide the energy necessary to reaccelerate the radio emitting electrons.

References

M. Bacchi, L. Feretti, G. Giovannini, F. Govoni, 2003, A&A 400, 465

B. Ballarati, L. Feretti, A. Ficarra, G. Giovannini, M. Nanni, C. Olori, G. Gavazzi, 1981, A&A 100, 323

P. Blasi & S. Colafrancesco, 1999, Astrop. Phys. 12, 169

P. Blasi, 2000, ApJL 532, L9

G. Brunetti, G. Setti, L. Feretti, G. Giovannini, 2001, MNRAS 320, 365

G. Brunetti, 2003, in *Matter and energy in clusters of galaxies*, eds. S. Bowyer & C.-Y. Hwang, ASP Conference Series, p. 349

C.L. Carilli & G.B. Taylor, 2002, ARA&A 40, 319

K. Dolag, S. Schindler, F. Govoni, L. Feretti, 2001, A&A 378, 777

T.A. Enßlin, P.L. Biermann, U. Klein, S. Kohle, 1998, A&A 332, 395

L. Feretti, D. Dallacasa, G. Giovannini, A. Tagliani, 1995, A&A 302, 680

L. Feretti, R. Fusco-Femiano, G. Giovannini and F. Govoni, 2001, A&A 373, 106

L. Feretti, 2002, in *The Universe at Low Radio Frequencies*, Proceedings of the IAU Symposium 199, eds. A. Pramesh Rao, G. Swarup & Gopal-Krishna, p.133

R. Fusco-Femiano, M. Orlandini, S. De Grandi, S. Molendi, L. Feretti, G. Giovannini, M. Bacchi, F. Govoni, 2003, A&A 398, 441

R. Fusco-Femiano, M. Orlandini, G. Brunetti, L. Feretti, G. Giovannini, P. Grandi, G. Setti, 2004, ApJ Letters, in press, astro-ph/0312625

G. Giovannini, L. Feretti, T. Venturi, K.-T. Kim, P.P. Kronberg, 1993, ApJ 406, 399

G. Giovannini & L. Feretti, 2002, in *Merging Processes of Galaxy Clusters*, eds. L. Feretti, I.M. Gioia & G. Giovannini, ASSL, Kluwer Ac. Publish., p. 197

F. Govoni, T. Ennßlin, L. Feretti, G. Giovannini, 2001, A&A 369, 441

F. Govoni & M. Murgia, 2004, in *Highlights of Astronomy*, Vol.13, in press, astro-ph/0311385

F. Govoni, M. Markevitch, A. Vikhlinin, L. VanSpeybroeck, L. Feretti, G. Giovannini, 2004, ApJ in press, astro-ph/0401421

J.C. Kempner & C.L. Sarazin, 2001, ApJ 548, 639

F. Miniati, T.W. Jones, H. Kang, D. Ryu, 2001, ApJ 562, 233

M. Markevitch & A. Vikhlinin, 2001, ApJ 563, 95

M. Markevitch, A. Vikhlinin, W.R. Forman, 2003, in *Matter and energy in clusters of galaxies*, eds. S. Bowyer & C.-Y. Hwang, ASP Conference Series, p. 37

V. Petrosian, 2001, ApJ 557, 560

L. Rudnick & K.M. Blundell, 2003, *ApJ* 588, 143

M. Thierbach, U. Klein, R. Wielebinski, 2003, A&A 397, 53

M.A.G. Willson, 1970, MNRAS 151, 1